BipolarPhysics

Thursday, January 14, 2021 9:02 AM

BipolarPhysics

PHYSICS OF BIPOLAR TRANSISTORS

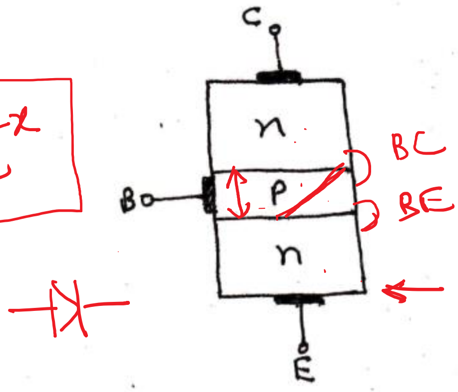
* A bipolar transistor consists of three doped regions forming a sandwich:-

Source ← ① Emitter. → emits charge carriers

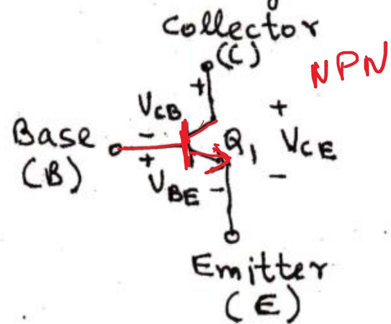
Gate ← ② Base → controls the ~~very~~ number of charge carriers making the journey.

Drain. ← ③ Collector → collects the charge carriers.

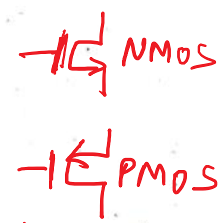
$\boxed{e^{-x}}$

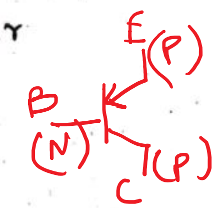


Structure



Symbol





* Two pn-junctions
  → between base-emitter
  → between base-collector.

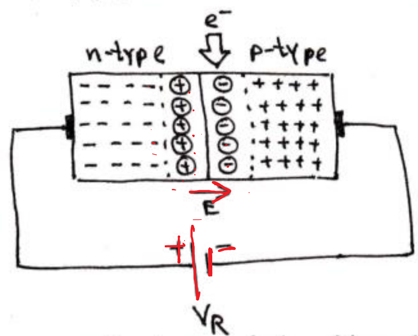
* The device is not symmetric with respect to emitter and collector.

* The dimensions and doping levels of emitter and collector are quite different.

* EMITTER AND COLLECTOR CANNOT BE INTERCHANGED.

* Proper operation of the device require that base be a thin region, eg. about 100 Å in modern integrated circuits.

Injection of electrons into depletion region :-



Lets inject an electron into the depletion region in a reverse biased pn-junction.

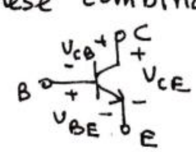
It serves as minority carrier in p-type and is rapidly swept away into n-side by the electric field.

* Ability of the reverse-biased pn-junction to efficiently "collect" externally-injected electrons /holes proves essential to the operation of bipolar transistors.

BJT	MOS
Active →	Saturation
Saturation →	Linear.
Cut-off →	Cut-off.

OPERATION OF BIPOLAR TRANSISTOR IN ACTIVE MODE :-

* In this mode the transistor acts a current source between collector and emitter.
* The above current is controlled by the voltage between base and emitter.
* For a bipolar transistor the terminal voltages V_{BE}, V_{BC}, and V_{CE}, which can assume positive and negative values, there are $\boxed{2^3}$ possible cases.
* One ~~is~~ of these combinations is useful.



← Active

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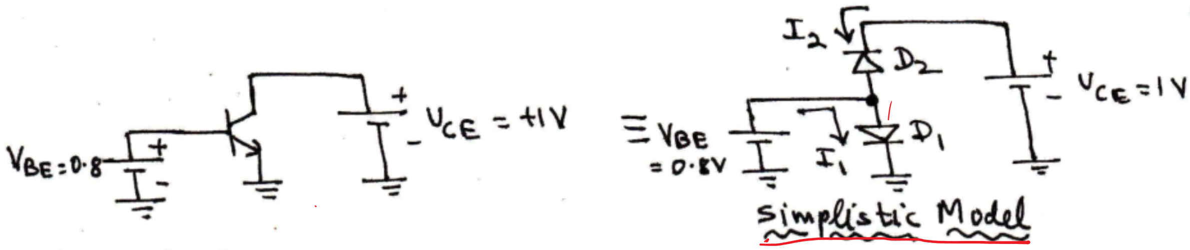


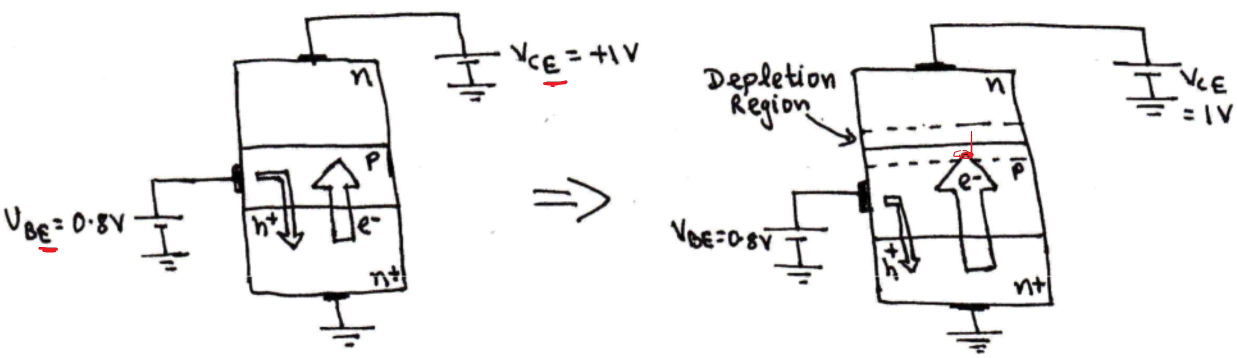
Circuit Condition :- $V_{BE} > 0$

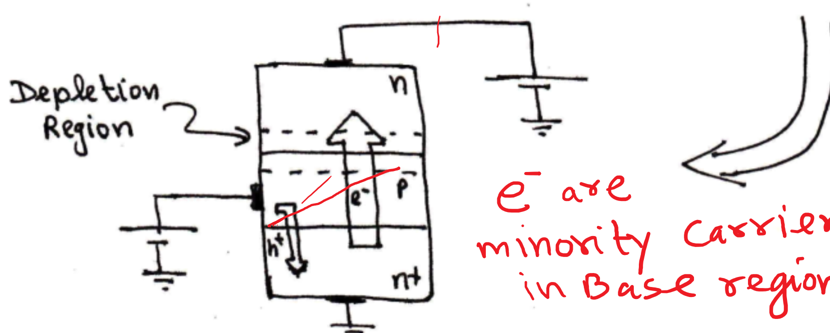
$V_{CE} > 0$

and $V_{BC} < 0$

* The simplistic model assumes that D_2 ~~is~~ should not carry any current and hence there cannot be any voltage to current conversion.

MOTION OF CARRIERS IN SLOW MOTION :-



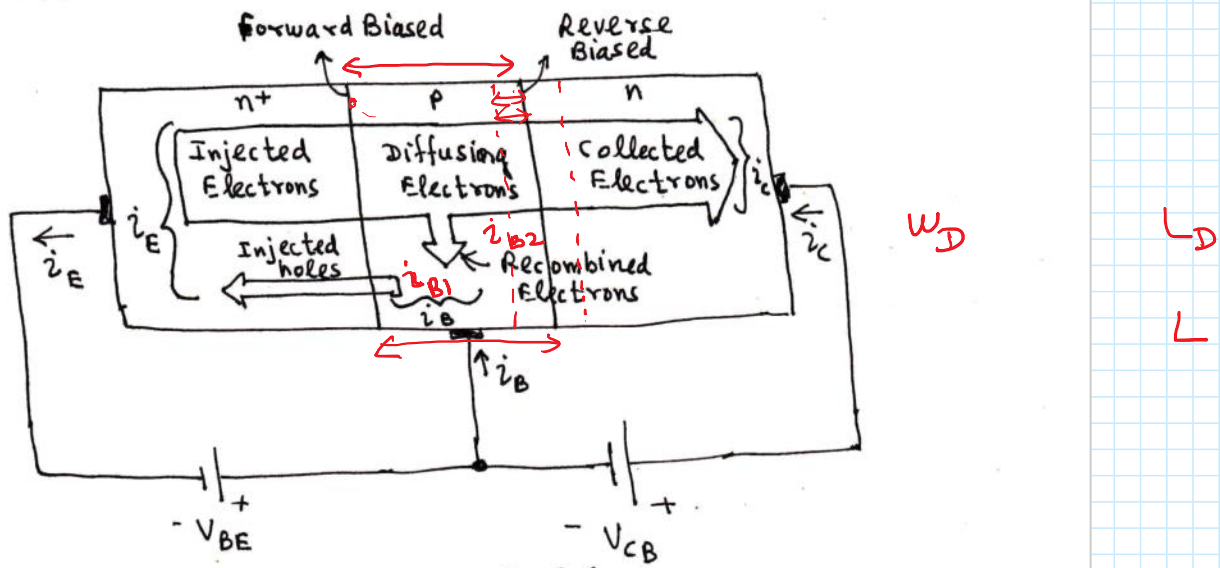


e^- are minority carriers for NPN in Base region.

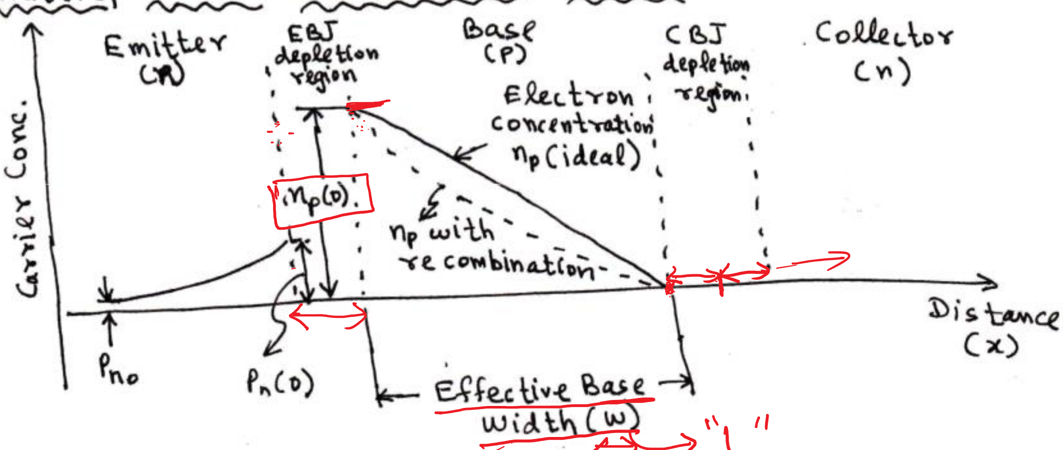
* Emitter is heavily doped.
* Base is thin.

④

Illustration of Current flow:-



Minority Carrier Concentration Profile:-



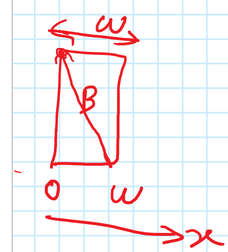
* Since base is very thin
  ⟹ Carrier concentration will be almost a straight line.

* why is the concentration "0" at CBJ, depletion region?
  → Since any electron reaching there is swept away by the electric field in depletion region the concentration falls to "0".

* What about recombination of electrons & holes in the base region?
  → Due to recombination the profile deviates from straight line ~~and becomes~~ slightly. We can ignore this while deriving the current.

* In a forward biased p-n junction the concentration,

$$n_p(0) = n_{po}\, e^{V_{BE}/V_T}.$$



where, n_{po} = thermal equilibrium value of minority-carrier concentration.

V_T = thermal voltage $\approx 25\,mV$. or $26\,mV$

V_{BE} = Forward biased base emitter voltage.

* The diffusion current in base region is,

$$I_n = A_E\, q\, D_n \frac{d\, n_p(x)}{dx}$$

$$\Rightarrow I_n = A_E\, q\, D_n \left(-\frac{n_p(0)}{W}\right)$$

where, A_E = cross-sectional area of BE junction.

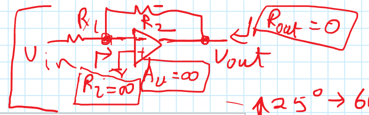
$q = 1.6 \times 10^{-19}\, c$

D_n = electron diffusivity in base.

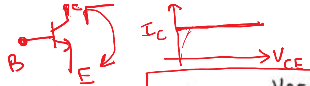
W = effective base width.

* The electrons diffusing through base get collected by the collector thus giving collector current as,

$$i_c = I_n.$$ ← collector current



$\uparrow 25° \rightarrow 60dB$
$\downarrow 25° \rightarrow 50dB.$



⑥

$\Rightarrow \boxed{i_c = I_s e^{V_{BE}/V_T}}$ $\rightarrow$ A_E & V_{BE}.

$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS}-V_{TH})^2$

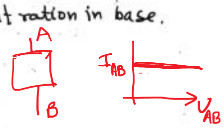
$\Rightarrow W, L, V_{GS}.$

$\mu_n C_{ox} \frac{W}{L}$

where, I_s = saturation current = $A_E q \, D_n \frac{n_{po}}{W}$.

Now, $n_{po} = \frac{n_i^2}{N_A}$, where n_i = intrinsic carrier concentration and N_A = doping concentration in base.

Thus, $I_s = \frac{A_E q D_n n_i^2}{N_A W}$.



R, C, VCCS or VCVS

BC junction

$\rightarrow$ NPN electrons get injected

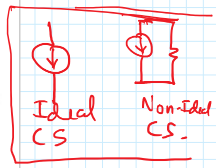
$\rightarrow$ PNP holes get injected

* I_s & i_c dependent on V_{CB}?? $\Rightarrow$ not dependent on CE-Voltage

No.

→ So what do we have?

→ A current source between collector & emitter.



* What about the base current?

It has two components:-

① Due to holes injected from base region to emitter. This is given by,

$$i_{B1} = \boxed{\frac{A_E q \, D_p n_i^2}{N_D L_p} e^{V_{BE}/V_T}}$$

excess

where, L_p = diffusion length (related to minority carrier ~~...~~ lifetime).

D_p = hole diffusivity.

N_D = doping concentration in emitter.

② Due to holes that have to be supplied by external circuit in order to replace holes lost from the base through recombination.

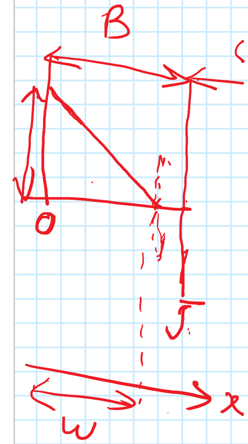
$$i_{B2} = \frac{Q_n}{\tau_b}$$

where, τ_b = average time for minority electron to recombine with majority hole in the base.

⑦

Q_n = minority carrier charge stored in the base.

$$\Rightarrow Q_n = A_E q \times \frac{1}{2} n_p(0) W \quad \ldots \text{[Area of triangle.]}$$



$$\Rightarrow Q_n = \frac{A_E q W n_i^2}{2 N_A} e^{V_{BE}/V_T} \quad \ldots \because n_p(0) = n_{p0} e^{V_{BE}/V_T}$$

$$\text{or, } n_p(0) = \frac{n_i^2}{N_A} e^{V_{BE}/V_T}$$

Thus, $$i_{B2} = \frac{1}{2} \frac{A_E q W n_i^2}{\tau_b N_A} e^{V_{BE}/V_T}$$

Hence, total base current is,

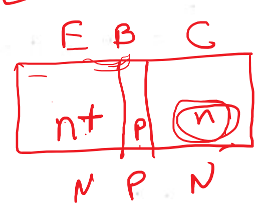
$$i_B = i_{B1} + i_{B2}$$

$$\Rightarrow i_B = I_S \left[\frac{D_p}{D_N} \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b} \right] e^{V_{BE}/V_T}.$$

We know, $$i_C = I_S e^{V_{BE}/V_T}.$$

50 to 200

Thus, $$i_B = \frac{i_C}{\beta}$$



where, $$\beta = \frac{1}{\left(\frac{D_p}{D_N} \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_N \tau_b} \right)}$$

$N_{D,C} < N_{D,E}$

* β is typically around 50 to 200.
* β is called common-emitter current gain.
  → what is β in a MOS??
* For high β :-
  → Base should be thin (W)
  → Emitter should be heavily doped than base i.e. $N_D \gg N_A$.

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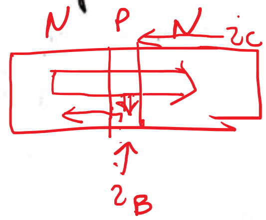
Emitter Current:- Since current entering a transistor must leave it, we have,

$$\boxed{i_E = i_C + i_B}$$



$$\Rightarrow i_E = (\beta+1)\, i_B.$$

$$\Rightarrow i_E = \frac{\beta+1}{\beta}\, i_C.$$

Sometimes i_c is expressed in terms of i_E leading to the following,

$$\boxed{i_C = \left(\frac{\beta}{\beta+1}\right) i_E}$$

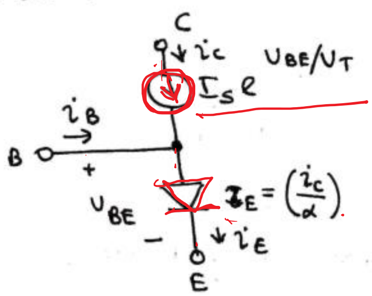
$\beta \rightarrow$ CE current gain.

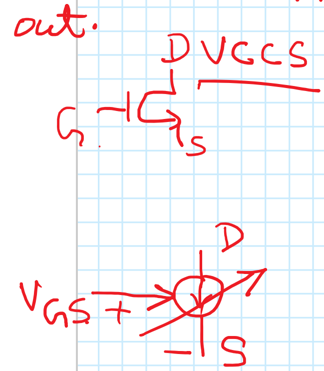
or, $i_C = \alpha\, i_E$ ... where, $\alpha = \dfrac{\beta}{\beta+1} \approx 1$ if β is large.

* $\boxed{\alpha = \text{Common Base Current Gain.}}$

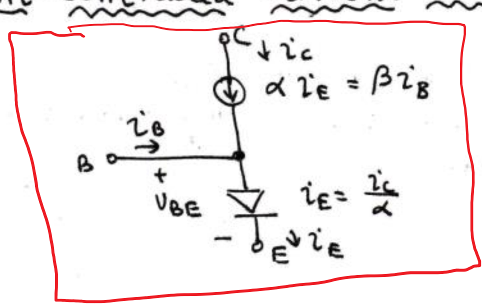
LARGE SIGNAL EQUIVALENT CIRCUIT MODEL ← exact expression of I–V .until transistor burns out.

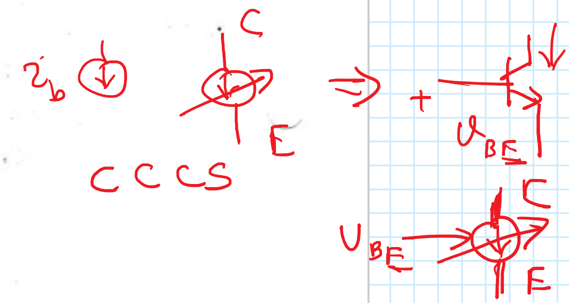
(i) Voltage-Controlled-Current Source :-





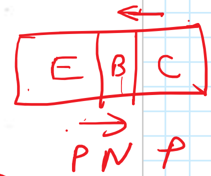
(ii) Current-Controlled Current Source :-





BJT Modes Of Operation :-

Mode	EBJ	CBJ
① Cutoff	Reverse	Reverse
② Active	Forward	Reverse
③ Reverse Active	Reverse	Forward
④ Saturation	Forward	Forward



$\boxed{\alpha, \beta}$

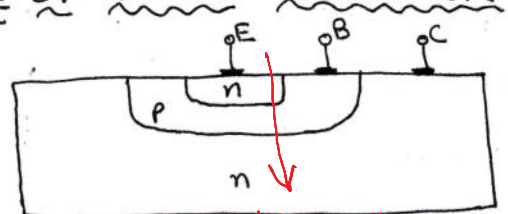
α_F, β_F

α_R, β_R

* The "α" and "β" derived earlier is for active mode also sometimes called "forward active" mode to distinguish it from "reverse active" mode.
* "α_F" & "β_F" are for "forward active" mode.
* "α_R" & "β_R" are for "reverse active" mode.
* If subscript is not given and α & β are given to you $\Rightarrow \left.\begin{array}{l}\alpha = \alpha_F \\ \beta = \beta_F\end{array}\right\}$

Note :- Since BJT is rarely used in reverse active mode, whenever we use "α" & "β" we mean "α_F" and "β_F".

Structure Of Actual Transistor :-



Cross-section view

Top View

* CBJ has a much larger area than EBJ.
* If the roles of collector and emitter are reversed then we say the transistor is in "reverse active" mode.
* So in reverse active mode we should have "α_R" and "β_R".

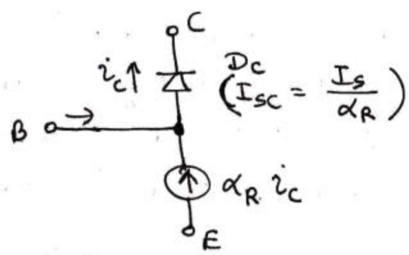
(10)

* Typically "α_R" is in the range 0.01 to 0.5 and "β_R" is in the range 0.01 to 1.

* "α_R" and "β_R" are few orders of magnitude lower than "α_F" and "β_F".

1 order lower ⇒ $\frac{1}{10}$
2 order lower ⇒ $\frac{1}{100}$
1 order higher ⇒ 10
2 orders higher ⇒ 100

LARGE SIGNAL MODEL FOR NPN TRANSISTOR IN REVERSE ACTIVE MODE :-



* which one is E & C?
* In case of MOS if 3-terminals only given the S & D are defined and therefore not interchngeable.

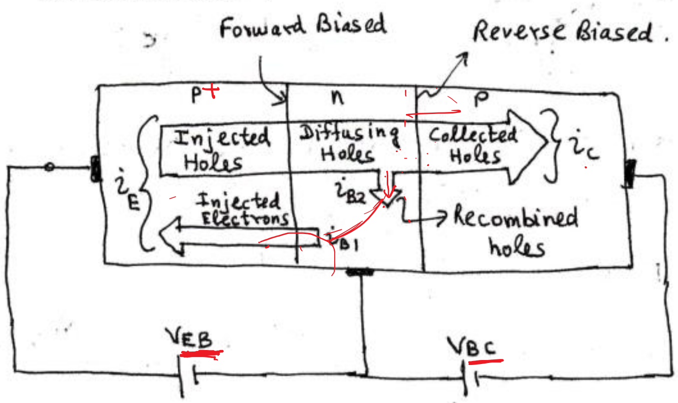
(13)

NOTE :-

SATURATION IN BJT ≡ TRIODE IN MOS

ACTIVE IN BJT ≡ SATURATION IN MOS

PNP TRANSISTOR :-



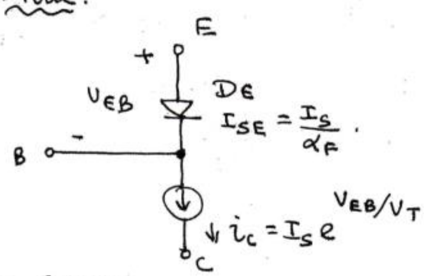
NMOS → V_{GS}, V_{DS}, V_{GD}, V_T is positive

PMOS → V_{SG}, V_{SD}, V_{DG}, V_T is negative.

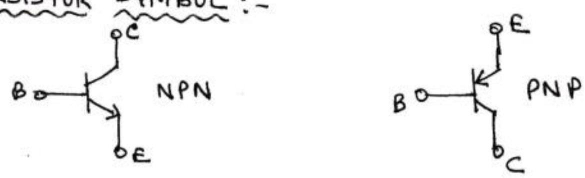
NPN → V_{BE}, V_{CE}, V_{CB}

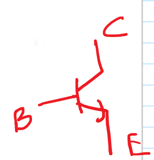
PNP → V_{EB}, V_{EC}, V_{BC}.

Large Signal Model for PNP transistor in Forward Active Mode :-



TRANSISTOR SYMBOL :-





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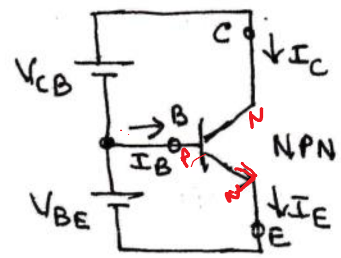
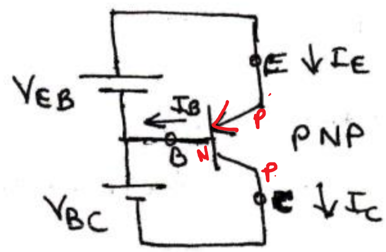
Voltage Polarities And Current Flow in Transistors biased in active mode:-





Summary Of BJT Current Voltage Relationship In Active Mode:-

① $I_C = I_S e^{V_{BE}/V_T}$

② $I_B = \frac{I_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{V_{BE}/V_T}$

③ $I_E = \frac{I_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{V_{BE}/V_T} = I_{SE}\, e^{V_{BE}/V_T}$

$\boxed{I_E = I_C + I_B}$

$\boxed{\text{For PNP, replace } V_{BE} \text{ with } V_{EB}}$

④ $I_C = \alpha I_E\,,\quad I_B = (1-\alpha) I_E = \frac{I_E}{\beta+1}$

⑤ $I_C = \beta I_B\,,\quad I_E = (\beta+1) I_B$

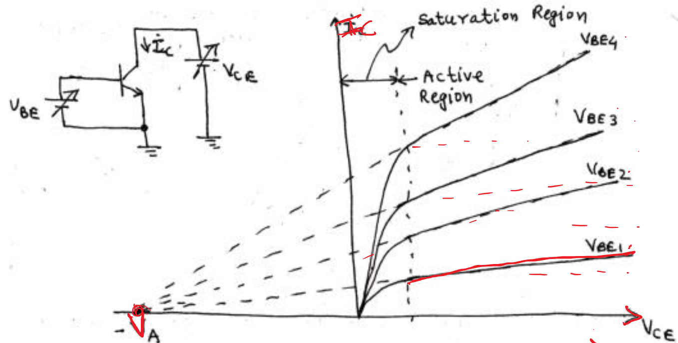
⑥ $\boxed{\beta = \frac{\alpha}{1-\alpha}}\,,\quad \boxed{\alpha = \frac{\beta}{\beta+1}}$.

$I_S = I_D + I_G$

$I_G = 0$

$\Rightarrow I_S = I_D$

DEPENDENCE OF I_C on COLLECTOR VOLTAGE – EARLY EFFECT:-



For a particular V_{BE} we have,

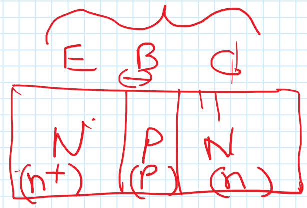
$$I_C = A_E q D_n \frac{n_{po}}{W} e^{V_{BE}/V_T}$$

$$\text{or, } I_C = \underbrace{A_E q \frac{D_n n_i^2}{N_A W}}_{I_S} e^{V_{BE}/V_T}$$

* We see, $I_S \propto \frac{1}{W}$ ⇒ if W reduces I_S increases.
* What defines W? i.e. effective base width?
* Increasing V_{CE} for particular V_{BE}, is going to increase CBJ depletion width ⇒ W reduces.
* If W reduces I_S increases ⇒ I_C increases.
* Discovered by, J.M. Early ⇒ found extrapolated characteristics all meet at one point called EARLY VOLTAGE.

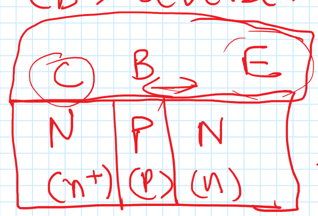
Base width gets modulated

⇒ I_C increases.



EB → forward biased

CB → reverse biased.



$I_C = I_B + I_E$

⇒ $I_E = I_C + I_B$

$I_C =$

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* The linear dependence of I_C on V_{CE} can be accounted by assuming I_S doesn't change but adding additional factor $\left(1+\frac{V_{CE}}{V_A}\right)$ to I_C as shown below:-

$$I_C = I_S e^{V_{BE}/V_T}\left(1+\frac{V_{CE}}{V_A}\right) \Rightarrow I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

* Since, I_C changes with V_{CE} there has to be a resistance associated with it and it is called the output resistance "r_o".

Unified approach to ckt analysis for analyzing both MOS & BJT

$$\boxed{r_o = \left[\left(\frac{\partial I_C}{\partial V_{CE}}\right)_{V_{BE}=\text{constant}}\right]^{-1}}$$

$$\Rightarrow r_o = \frac{V_A}{I_C} \Rightarrow r_o = \frac{1}{\lambda I_D} \Rightarrow \lambda = \frac{1}{V_A}.$$

without channel length modulation.

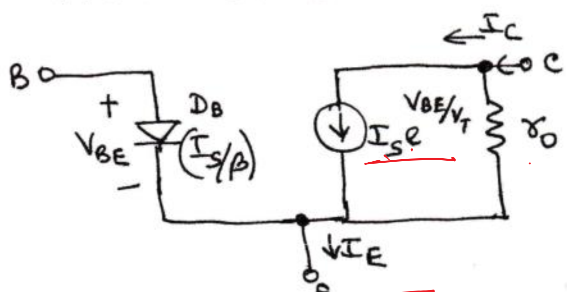
~~Typically $V_{CE} \ll V_A$, thus,~~

where, $\boxed{I_C = I_S e^{V_{BE}/V_T}}$ is the current with "Early Effect" neglected.

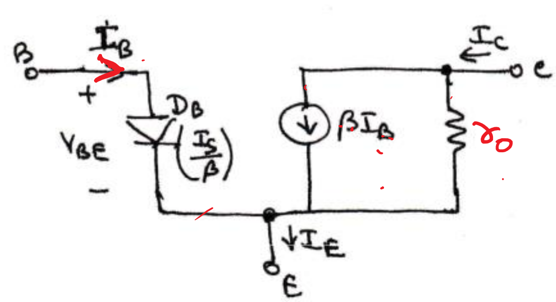
$I_G = 0$

$I_B \neq 0$

* LARGE SIGNAL MODEL WITH EARLY EFFECT:-

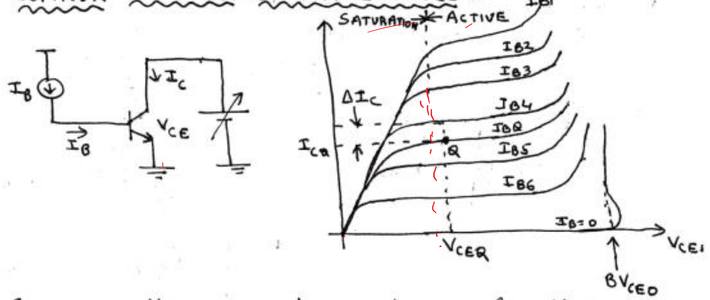


VCCS Model

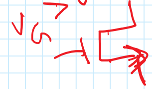


CCCS Model

Common Emitter Characteristics :-

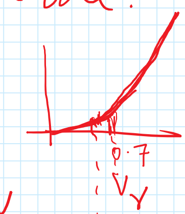


$V_G > V_D$ by V_{TH}

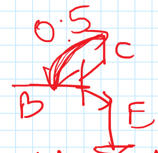


$V_G > V_S$ by V_{TH}

Triode.



V_γ.



$V_{CE} \approx 0.2V.$

* Common emitter current gain is simply called β (to be more precise β_F). β_F

* At the operating point,

$$\beta_{dc} \equiv \frac{I_{CQ}}{I_{BQ}}$$

This is called large signal or dc β.

β_{DC}

$\beta_{AC}.$

$$\frac{I_C}{I_B} = \beta_{DC}$$

$V_B = V_E + 0.7 \Rightarrow V_B = 0.7$

Cut-in voltage of diode.

* Incremental or ac β is given by,

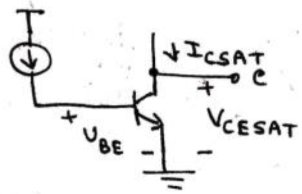
$$\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = \text{constant}}.$$

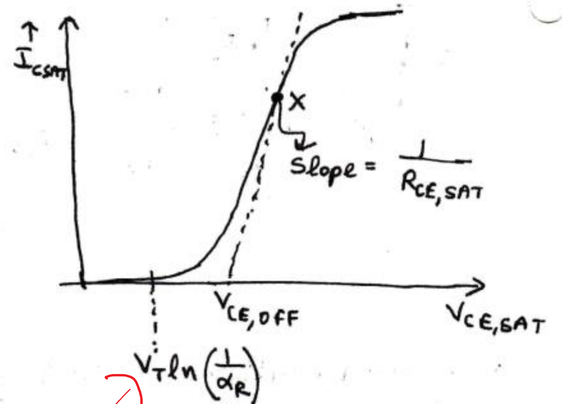
$$\boxed{\frac{I_C \pm \Delta I_C}{I_B \pm \Delta I_B}} \Rightarrow \beta_{AC} = \frac{\Delta I_C}{\Delta I_B}$$

* β_{ac} and β_{dc} differ in magnitude by approx. 10 to 20%.
* For this course, β_{ac} and β_{dc} will not be differentiated i.e. we won't make a distinction between the two.

$\beta_{AC} = \beta_{DC}$ for this course.

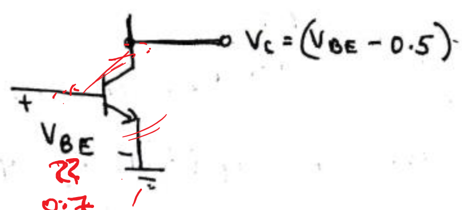
* Just like a MOSFET in triode region a saturated BJT acts like a resistor.





$$R_{CE,SAT} = \left.\frac{\partial V_{CE}}{\partial I_C}\right|_{\substack{I_B = \text{some value} \\ I_C = I_{CSAT}}}$$

* Note that Base-Collector junction get forward biased and carries substantial current when base is greater than collector by 0.5 Volts atleast.



⇒ $V_{CE,SAT} \simeq 0.2V$

$V_{D,SAT} = (V_{GS} - V_{TH})$ for long channel

(20)

SMALL SIGNAL OPERATION AND MODELS:-

Convention:-

$\rightarrow v_{BE} = \underset{\downarrow}{\overset{DC}{}}V_{BE} + \underset{\downarrow}{\overset{AC}{}}v_{be}$

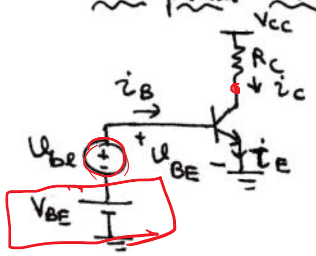
$\rightarrow v_{CE} = V_{CE} + v_{ce}$

$\rightarrow i_C = I_C + i_c$

$\rightarrow i_B = I_B + i_b = 0$ in case of MOS.

$\rightarrow i_E = I_E + i_e$

Conceptual circuit to arrive at small signal model:-



At DC (i.e. no ac signal applied).

$$\underline{I_C = I_s e^{V_{BE}/V_T}}$$

$$\underline{I_E = I_C/\alpha}$$

$$\underline{I_B = I_C/\beta}$$

$$V_C = V_{CE} = V_{CC} - I_C R_C$$

With ac signal:-

$$v_{BE} = V_{BE} + v_{be}$$

$$\Rightarrow i_C = I_C + i_c$$

$$\Rightarrow i_C = I_s e^{(V_{BE} + v_{be})/V_T}.$$

$$\Rightarrow i_C = \underline{I_s e^{V_{BE}/V_T}}\, \underline{e^{v_{be}/V_T}}$$

$v_{gs} < 2v_{ov}.$

$$\Rightarrow i_C = \boxed{I_C} e^{v_{be}/V_T}$$

$$\Rightarrow i_C = I_C \underbrace{\left(1 + \frac{v_{be}}{V_T}\right)}$$

... (By Taylor series expansion with $\frac{v_{be}}{V_T} << 1$)

$\boxed{v_{be} << V_T}$

(21)

$$i_c = I_C\left(1 + \frac{v_{be}}{V_T}\right)$$

Thus, $$i_c = I_c + \boxed{\frac{I_c}{V_T}} v_{be}$$

$\Rightarrow$ small signal, $i_c = \boxed{\frac{I_c}{V_T} v_{be}}$

$$I_c = I_s e^{v_{be}/V_T}.$$

$$\Rightarrow \frac{\partial I_c}{\partial V_{BE}} = \frac{I_s}{V_T} e^{v_{be}/V_T}$$

$$= \frac{I_c}{V_T}$$

$\Rightarrow$ $\boxed{\text{Transconductance, } g_m = \frac{I_c}{V_T}.}$

* Can you prove that, $g_m = \left.\frac{\partial i_c}{\partial V_{BE}}\right|_{i_c = I_c}$?

Now, $$i_c = I_s e^{V_{BE}/V_T}$$

$$\Rightarrow \frac{\partial i_c}{\partial V_{BE}} = \frac{I_s}{V_T} e^{V_{BE}/V_T}$$

$$\boxed{\Rightarrow \frac{\partial i_c}{\partial V_{BE}} = \frac{I_c}{V_T}.}$$

r_o

* Unlike MOSFET where there is no gate current at DC, we have a base current in BJT at DC.

* Now,

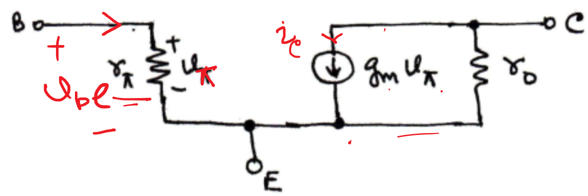
$$i_B = I_B + i_b$$

$$\Rightarrow i_B = \frac{I_c}{\beta} + \frac{I_c}{\beta V_T} v_{be}$$

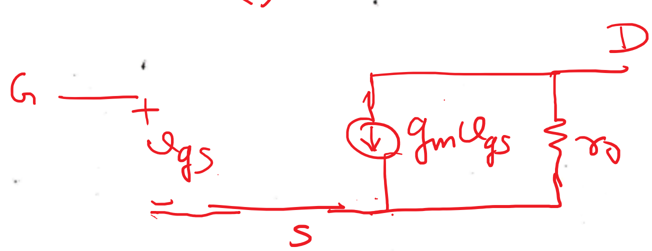
Thus, $$i_b = \frac{g_m}{\beta} v_{be}$$

$$\Rightarrow \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = r_\pi$$ = small signal input resistance between base and emitter.

Thus, small signal model of BJT is as follows:-



BJT Amp. → Counterpart in MOS.



edge of saturation in MOS → pinch-off happens @ Drain end $\Rightarrow \left(V_{DS} = \underbrace{V_{GS} - V_{TH}}_{V_{D,SAT}} \right)$

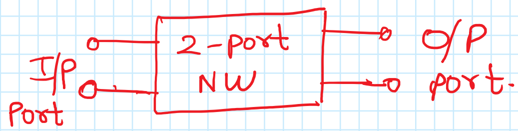
edge of active in BJT → $V_{CE} = \underbrace{0.2\,V}_{V_{CE,SAT}}$.

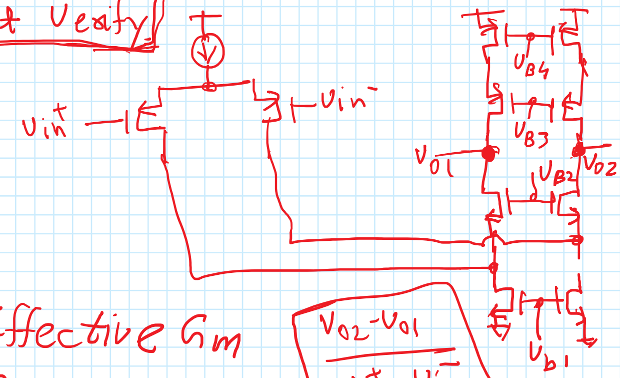
Friday, January 15, 2021 12:42 PM

OBTAINING GAIN OF A TWO PORT NETWORK (N/W):-

SUCCESSFUL FAILURE

Trust But Verify





$$\boxed{\frac{V_{o2}-V_{o1}}{v_{in}^{+}-v_{in}^{-}}}$$

A_v = Voltage Gain = $G_m R_{out}$.

G_m = Short Circuit Current Gain = Effective G_m

R_{out} = o/p resistance. = Effective R_{out}.

$G_m \Rightarrow$ (1) AC short @ o/p, (2) apply v_{in} @ i/p. and (3) obtain the short circuit current. (I_{sc})

$$G_m = \frac{I_{sc}}{V_{in}}$$

$R_{out} \Rightarrow$ (i) Apply test voltage (v_x) at o/p

(ii) Remove all independent voltage sources by shorting them out.

Remove all independent current sources by opening them

(iv) Leave all dependent voltage & current sources as they are.

(v) Solve for current flowing through v_x and call that as i_x.

$$\Rightarrow R_{out} = \frac{v_x}{i_x}.$$

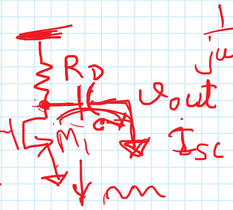
$$\boxed{R_{out} = \frac{v_x}{i_x}.}$$

AC Short what is it??

$v_{in} =$ ... 0

$v_{IN} =$ V_{IN}

V_{IN} ——— v_{in}



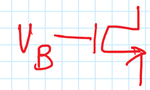
$\frac{1}{j\omega C}$

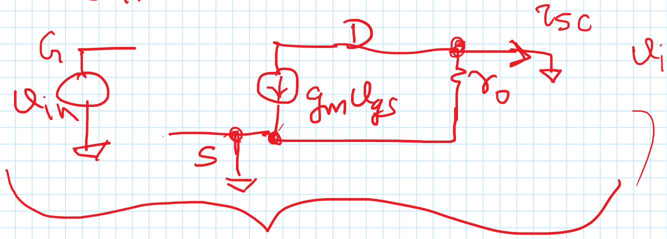
M_1

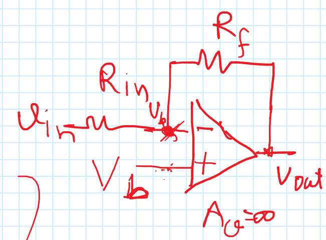
$v_{IN} = V_{IN} + v_{in}.$

* M_1 is in saturation

$\frac{i_{sc}}{v_{in}} = G_m$



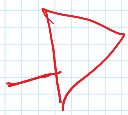




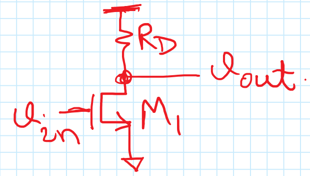
* DC Ground
* AC Ground
* Virtual Ground

* DC Ground is absolute ground

* AC Ground is any node that does not have a change in voltage



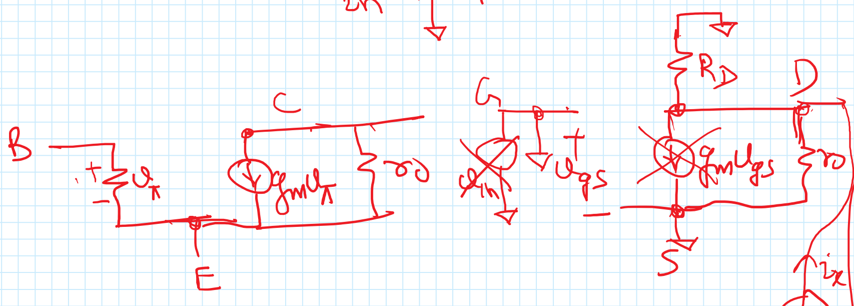
→ R_{out} ⇒

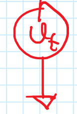


* Find gain
* Find i/p impedance
* Find o/p impedance

} The circuit is biased & the operating point is set properly.

⇓





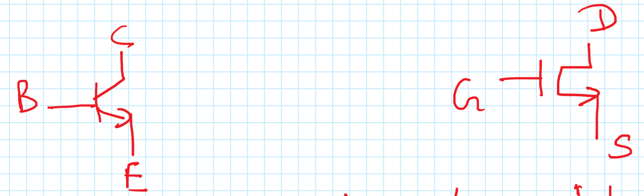
$$\frac{v_t}{i_x} = (r_o \| R_D)$$

	BJT	MOS
1	Active (Forward)	Saturation
2	I_C	I_D
3	& V_{CE} (V_{EB}) & (V_{EC})	V_{GS} & V_{DS} (V_{SG}) & (V_{SD})
4	$\frac{I_C}{V_T}$	$g_m = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{th})$
5	$r_o = \frac{V_A}{I_C}$	$r_o = \frac{1}{\lambda I_D}$

* Simple ckts using small signal model.

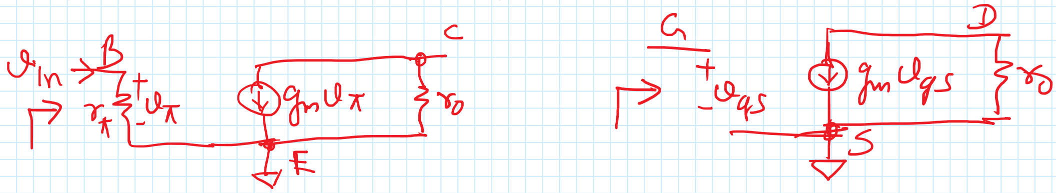
* For complex ckts use above results & find out A_v, R_{in}, R_{out} w/o small signal model.

* Resistance looking into various terminals of BJT & MOS:-



(i) Resistance looking into B/G: with E/S grounded:-

* we do not care where C/D is connected.



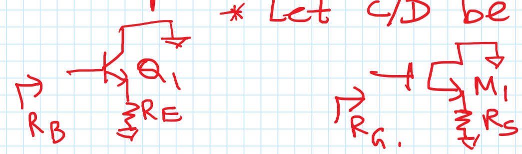
$R_B = r_\pi$

$R_G = \infty$

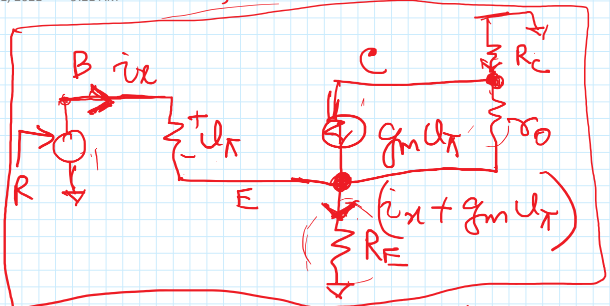
(ii) Resistance looking into B/G with E/S connected to ground via a resistor;

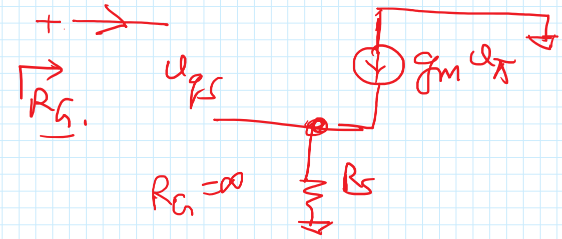
* Let C/D be connected to AC ground.

* Let Q_1/M_1 be ideal transistor, $V_A = \infty$ / $\lambda = 0$



If BJT is not ideal $\Rightarrow V_A \neq \infty$ then, $R_B = r_\pi + (R_E \| r_o)[1+\beta]$





$$v_\pi = v_x - (i_x + g_m v_\pi) R_E.$$

$$\Rightarrow v_\pi (1 + g_m R_E) = v_x - i_x R_E.$$

$$\Rightarrow i_x r_\pi (1 + g_m R_E) = v_x - i_x R_E$$

$$\Rightarrow i_x [r_\pi + g_m R_E r_\pi + R_E] = v_x.$$

$$\Rightarrow \frac{v_x}{i_x} = r_\pi + R_E(1 + \underbrace{g_m r_\pi}_{\beta}) \Rightarrow \boxed{R_B = r_\pi + R_E(1+\beta)}$$

* r_o of BJT is of 10's of $k\Omega$.

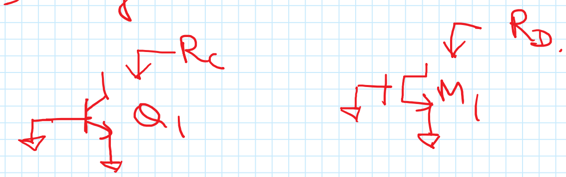
$$\boxed{r_o \gg R_E. \quad \Rightarrow (r_o \| R_E) \approx R_E}$$

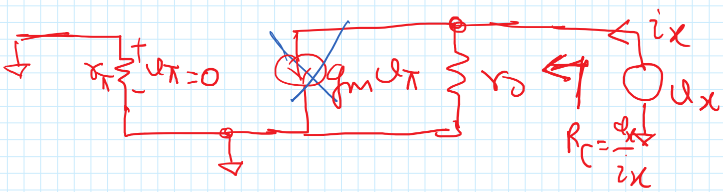
Typically, $R_E < 1k\Omega$ of the order 100Ω to 500Ω.

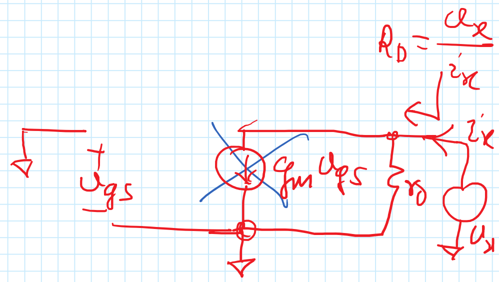
* Prove that in presence of $R_C \Rightarrow R_B \cong r_\pi + R_E(1+\beta)$.

* Resistance looking into collector/Drain:-

Case 1 :- E/S is grounded.





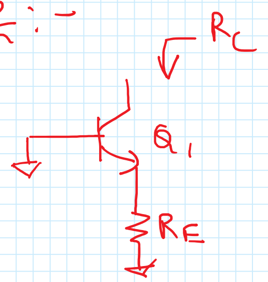


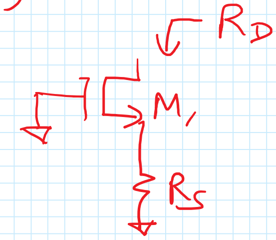
$$R_C' = \frac{v_x}{i_x} = r_o$$

$$R_D = \frac{v_x}{i_x} = r_o.$$

If Q_1/M_1 is ideal $\Rightarrow R_C = \infty$ and $R_D = \infty$.

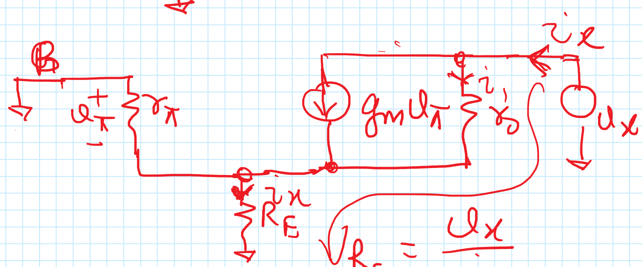
Case 2:-



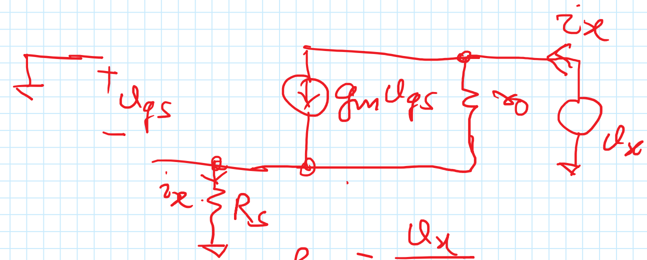


$i_1 r_o + i_x(R_E \| r_\pi) = v_x$.

$\Rightarrow \dfrac{v_x}{i_x} = (R_E \| r_\pi) + [1 + g_m(R_E \| r_\pi)] r_o$



$R_C = \dfrac{v_x}{i_x}$



$R_D = \dfrac{v_x}{i_x}$.

* What is R_C?

$v_\pi = -i_x(R_E \| r_\pi)$

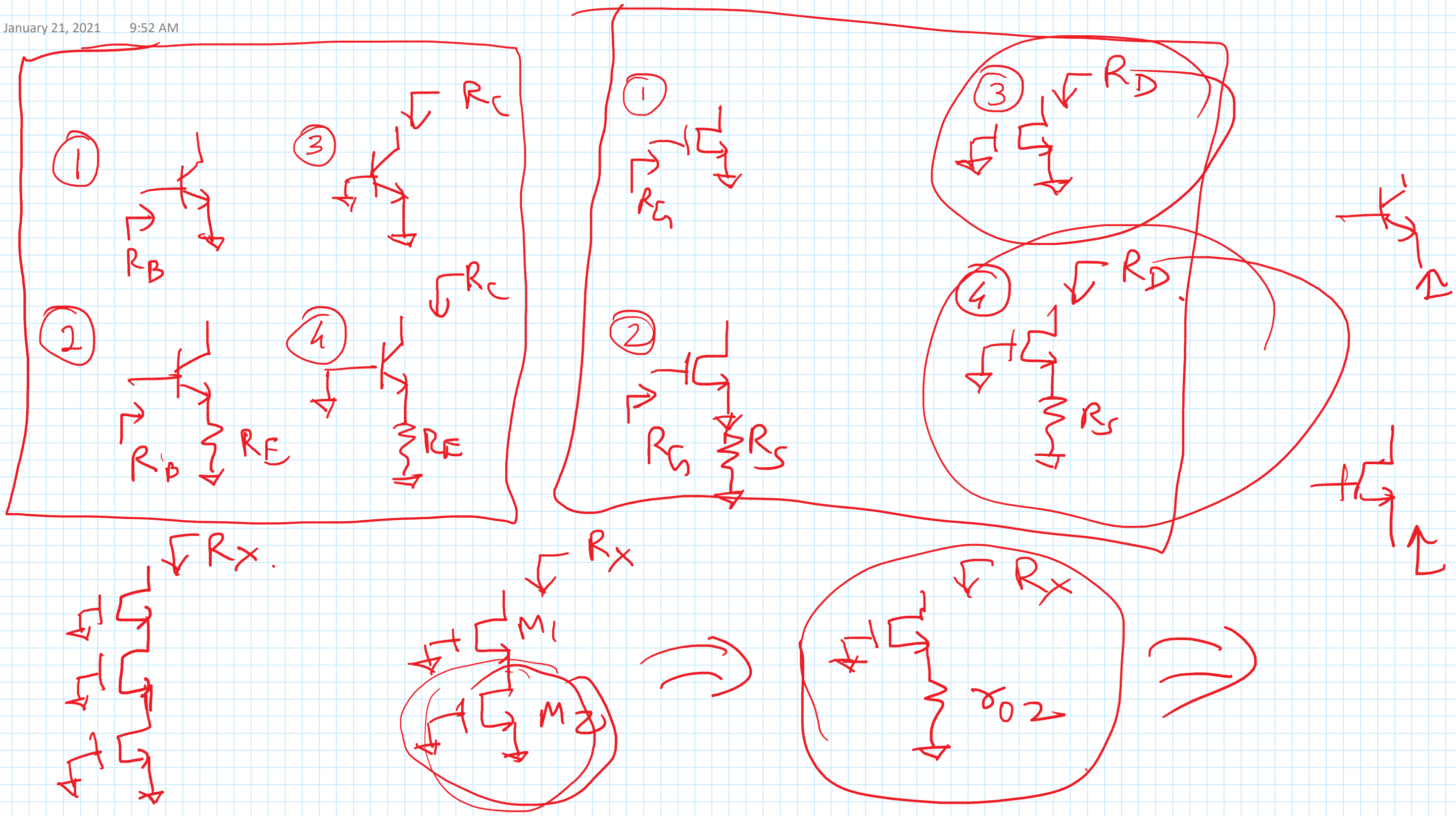
$i_1 = g_m i_x (R_E \| r_\pi) + i_x$.

$\Rightarrow i_1 = [g_m(R_E \| r_\pi) + 1] i_x$

* What is R_D??

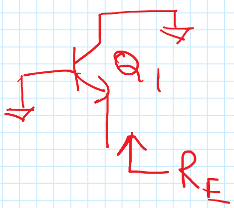
$R_D = r_o + g_m r_o R_S \simeq g_m r_o R_S$

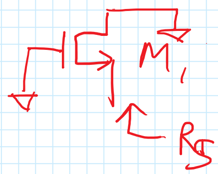
$\dfrac{v_x}{i_x} = R_S + (1 + g_m R_S) r_o$.


1
2
3
4
R_B
R_B
R_E
R_E
R_C
R_C
R_G
R_G
R_S
R_S
R_D
R_D
R_X
R_X
R_X
M_1
M_2
r_{o2}

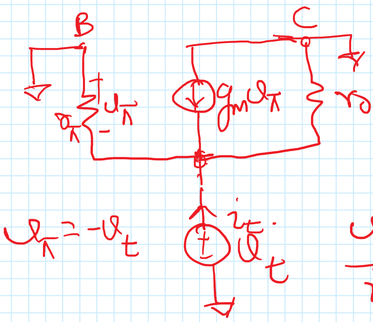
Resistance Looking into E/S :-

(i)





$$R_E = \left(\frac{1}{g_m} \| r_\pi \| r_o\right) \qquad R_s = \left(1/g_m \| r_o\right) \approx \frac{1}{g_m}.$$



$v_\pi = -v_t$

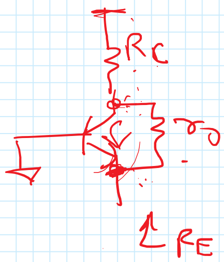
$$\frac{v_t}{i_t} = \left(\frac{1}{g_m} \| r_\pi \| r_o\right) \approx \frac{1}{g_m}$$

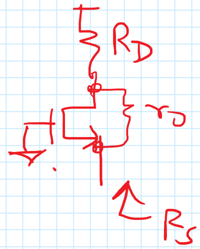
Typically $r_o = 1k\Omega$ to $1M\Omega$.

$r_\pi = 10$'s of $k\Omega$.

$\frac{1}{g_m} = (10 \text{ to } 100)\Omega$

(ii)





* Solve for R_E & R_S??

* Make appropriate ~~ap~~approx..

$\sin\theta = \theta$?? if θ is small??

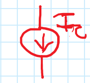
$\sin 1^\circ = 1^\circ$ $\Rightarrow$

$A_v = G_m \underbrace{R_{out}}$;

$\boxed{\beta_{AC} \simeq \beta_{DC}.}$

β_{DC}

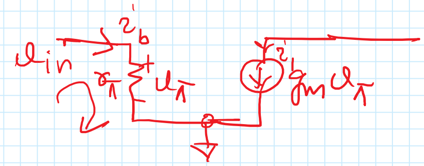
$\beta =$



$g_m = \frac{I_C}{V_T}$

$\boxed{r_\pi \cancel{g_m} = \beta.}$

$\Rightarrow$



$v_{in} = v_\pi$

$i_1 = g_m v_\pi$

$i_1 = \beta i_b = \beta \frac{v_{in}}{r_\pi}$

$\Rightarrow i_1 = g_m \cancel{v_\pi} = \beta \cancel{v_{in}}/r_\pi$

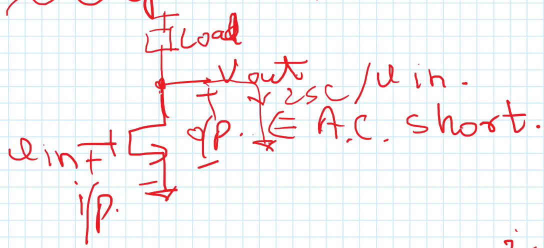
Def^n of ideal transistor $\Rightarrow$ $V_A = \infty$ for BJT, $\lambda = 0$ for MOS.

BJT	MOS
(1) Looking into Base. (i) (ii) Approx. for ideal transistor	(1) Looking into Gate Approx. for ideal transistor.
(2) Looking into collector (i) (ii) * Ideal tran. approx.	(2) Looking into Drain. (i) (ii) * Ideal tran. approx.
(3) Looking into emitter (i) (ii) * Ideal tran. approx.	(3) Looking into source. (i) (ii) * Ideal trans. approx.

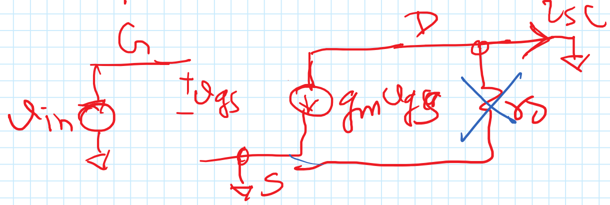
Friday, January 22, 2021 11:43 AM

2-Port NW $\Rightarrow A_v = G_m R_{out}$.

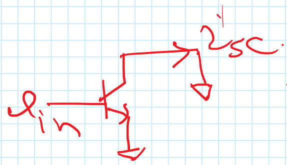
* Solving for effective G_m:-



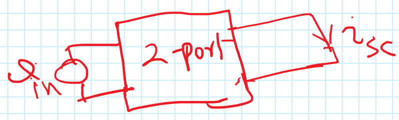
* Find o/p node.
* Put an a.c. short @ o/p.
* ~~Dod~~ Draw small signal model.
* Find i_{sc}/v_{in}.



$$G_m = \frac{i_{sc}}{v_{in}} = g_m.$$

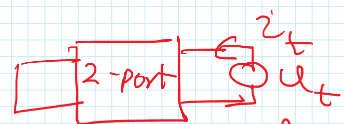


$$\Rightarrow G_m = \frac{i_{sc}}{v_{in}} = g_m.$$

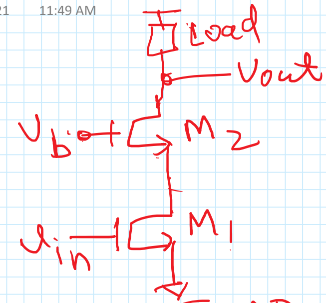


$$G_m = \frac{i_{sc}}{v_{in}}$$

$$A_v = G_m R_{out}.$$

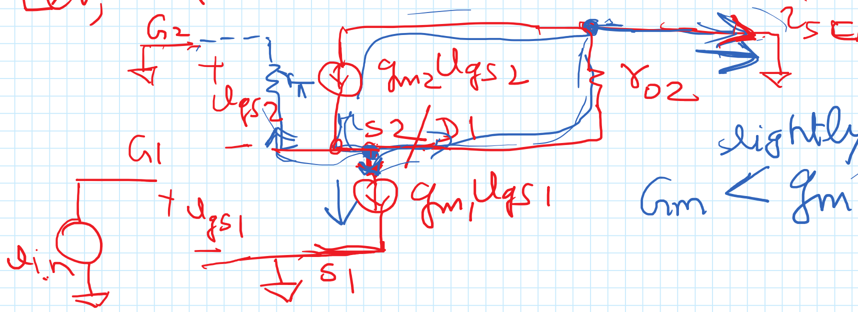


$$R_{out} = \frac{v_t}{i_t}.$$

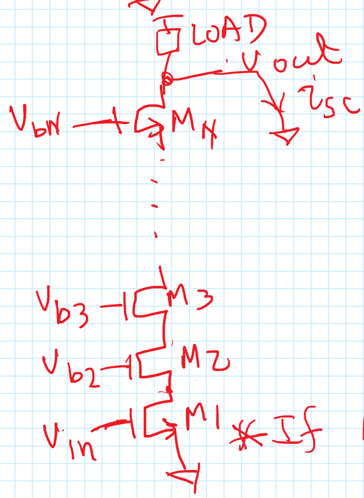


* V_b is bias voltage ⇒ A.C. ground.

* Let, M_1 be an ideal transistor.



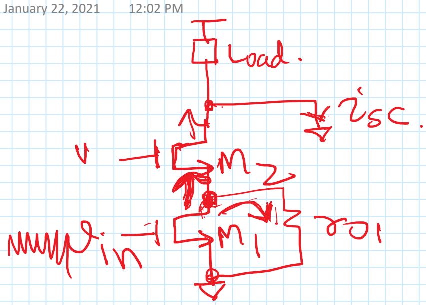
slightly
$G_m < g_{m1}$



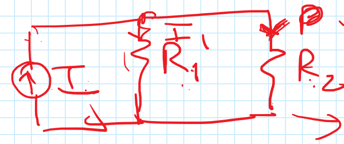
$$i_{sc} = g_{m1} v_{gs1} = g_{m1} v_{in}$$

$$\Rightarrow \frac{i_{sc}}{v_{in}} = G_m = g_{m1}.$$

* If M_1 is ideal. what is $G_m = g_{m1}$



If M_1 is not ideal??



$$I_2 = \frac{R_1}{R_1+R_2} I$$

$$I = g_{m1} v_{in}$$

$$G_m \approx g_{m1}.$$

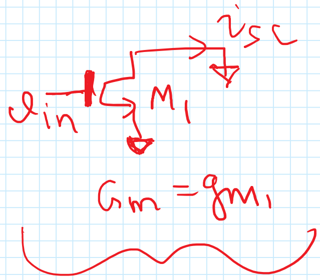
$$i_{sc} = \frac{r_o}{r_o + R_x} g_{m1} v_{in}. = \frac{r_o}{r_o + \left(\frac{1}{g_{m2}} \| r_{o2}\right)} g_{m1} v_{in}.$$

resistance looking into ~~M2~~ source of M_2 when drain of M2 is grounded.

$$G_m = \frac{i_{sc}}{v_{in}} = \frac{r_{o1}}{r_{o1} + \left(\frac{1}{g_{m2}} \| r_{o2}\right)} g_{m1}.$$

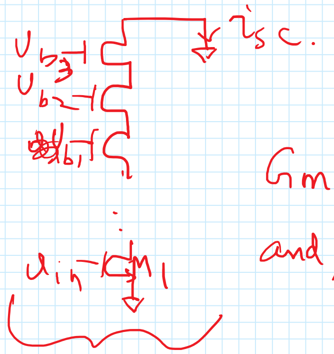
MOSFET ⇒ BJT case is your job.

(i)



$G_m = g_{m1}$

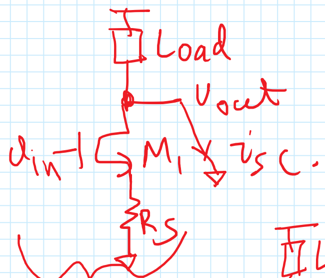
(ii)



$G_m \approx g_{m1}$ if $\lambda \neq 0$.

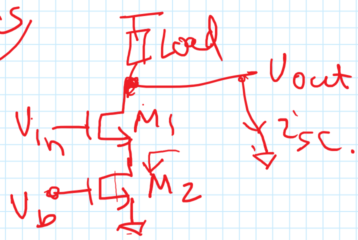
and, $G_m = g_{m1}$ if $\lambda = 0$.

(iii)

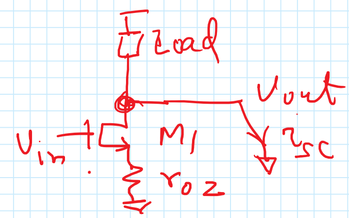


$$G_m \cong \frac{g_{m1}}{1 + g_{m1} R_S}$$

R_S can be a transistor in saturation.



$\approx$



$$\approx G_m = \frac{g_{m1}}{1 + g_{m1} r_{o2}}$$

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$|A_v| = G_m R_{out}$

G_m: effective

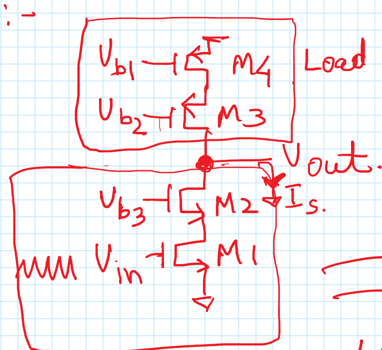
R_{out} → ~~R_{out}~~. effective o/p resistance

(i) Transistor is ideal ⇒ $V_A = \infty$ for BJT, $\lambda = 0$ for MOSFET

(ii) Transistor is real

Example 1 :-

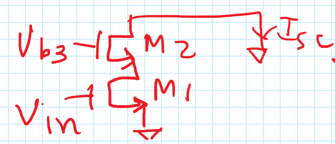
Find the voltage gain, $\lambda \neq 0$.



Input section.

(i) Find effective G_m:-

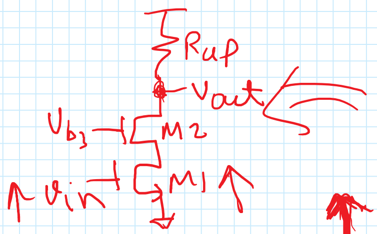
* We do not care what is in the load.

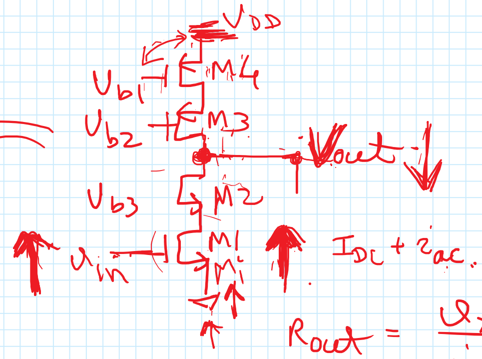


⇒ $G_m \approx g_{m1}$.

(ii) How to find R_{out}??

$v_{out} = v_{DD} - i_{M1} * R_{up}$





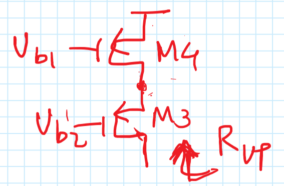
$$\boxed{\frac{v_x}{i_{up}} = R_{up}}$$

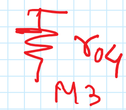
$$\Rightarrow R_{out} = R_{up} || R_{DN}$$

$$\frac{v_x}{i_{DN}} = R_{DN}$$

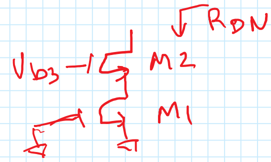
$$R_{out} = \frac{v_x}{i_x}$$

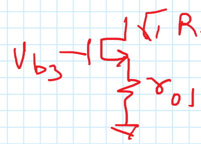
$$\boxed{A_v \cong -g_{m1} \cdot (g_{m3} r_{o3} r_{o4}) || (g_{m2} r_{o2} r_{o1})}$$





$R_{up} \cong g_{m3} r_{o3} r_{o4}$





$R_{DN} \cong g_{m2} r_{o2} r_{o1}$

$$R_{out} = (g_{m3} r_{o3} r_{o4}) || (g_{m2} r_{o2} r_{o1})$$

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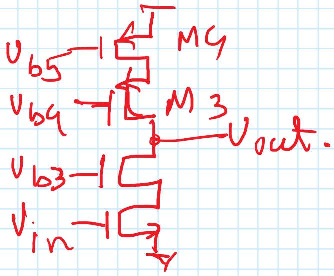
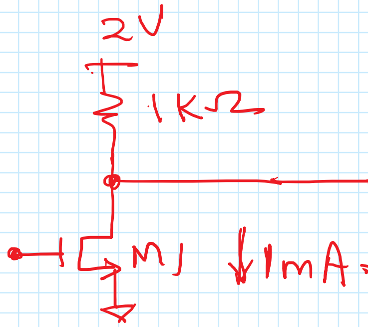


1.1V.

↑

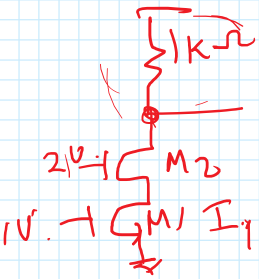
1V.



$V_{out} = 1V. \downarrow 900mV.$

↓1mA → ↑1.1mA.

3V. $\Delta V_{out} = -100mV$



$V_{out} = 2V.$

1.9V.

$I_q = 1mA$

↓ 1.1mA

↑ 1.1V.

+100mV.

+100μA.

$V_{IN} = 1V.$

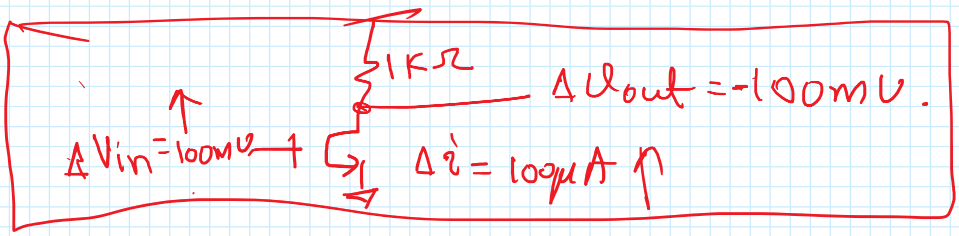
$I_{M1} = 1mA.$

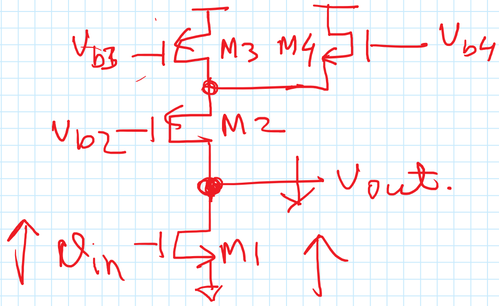
$V_{out} = 1V.$

$V_{IN}^{new} = 1.1V.$

$I_{M1}^{new} = 1mA$

$V_{out}^{new} = 900mV.$





Find A_v if $\lambda \neq 0$?

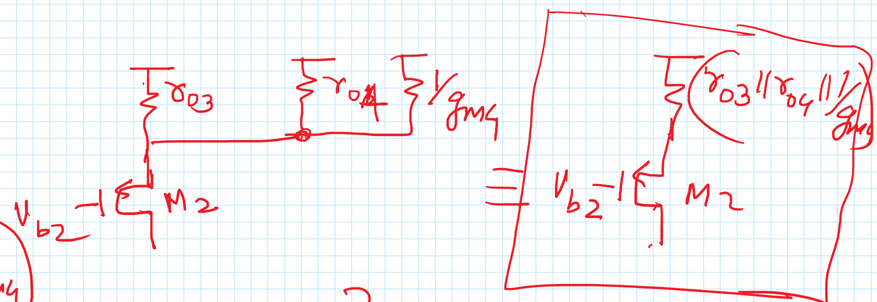
What is G_m??

What is R_{up}??

What is R_{DN}??

$$G_m = g_{m1}.$$

$$R_{DN} = r_{o1}.$$



$$R_{up} \cong g_{m2} r_{o2} \left(r_{o3} \| r_{o4} \| \frac{1}{g_{m4}} \right)$$

$$R_{out} = \left\{ r_{o1} \| \left[g_{m2} r_{o2} \left(r_{o3} \| r_{o4} \| \frac{1}{g_{m4}} \right) \right] \right\}$$

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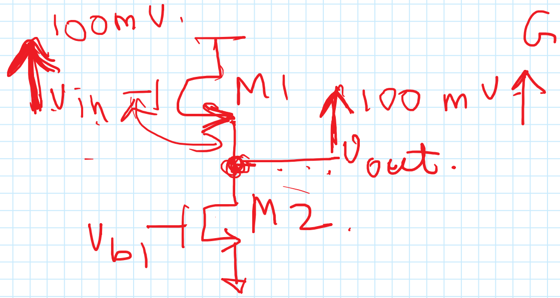

$\lambda = 0$

$G_m \cong g_{m1}$??

$R_{up} = \left(\frac{1}{g_{m1}} \| r_{o1}\right)$?? $\approx \frac{1}{g_{m1}}$

$R_{DN} = r_{o2}$??

$$\underbrace{A_v = + g_{m1} \cdot \left(\frac{1}{g_{m1}} \| r_{o2}\right) \approx 1}$$

Source Follower
Emitter Follower.

$100 \| 1000$
$\simeq 990$